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Short Communication

Resource depletion potentials from bottom-up models: Population dynamics and the Hubbert peak theory

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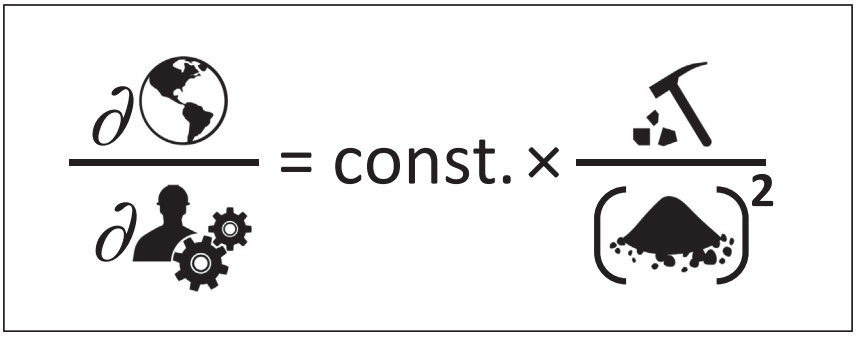
HIGHLIGHTS

- The resource issue is relevant in life cycle impact assessment.
- The historical development of resource depletion potentials is presented.
- A 20-year old speculation on this is connected with a recent paper on fish stock.
- Biotic resource assessment matches with this population dynamic based assessment.
- Abiotic resource assessment matches using the Hubbert peak theory.

GRAPHICAL ABSTRACT



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ABSTRACT

Life cycle impact assessment uses so-called characterization factors to address different types of environmental impact (e.g. climate change, particulate matter, land use…). For the topic of resource depletion, a series of proposals was based on heuristic and formal arguments, but without the use of expert-based models from relevant research areas. A recent study in using fish population models has confirmed the original proposal for characterization factors for biotic resources of the nineties. Here we trace the milestones of the arguments and the designs of resource depletion, delivering an ecological-based foundation for the biotic case, and extend it by a novel analysis of the Hubbert peak theory for the abiotic case. We show that the original abiotic depletion potential, used for two decades in life cycle assessment, estimates accurately a marginal depletion characterization factor obtained from a dynamic model of the available reserve. This is illustrated for 29 metal resources using published data.
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1. Introduction

Life Cycle Assessment (LCA) quantifies the environmental drawbacks of human activities, such as products and policies, in a system-wide perspective (ISO, 2006a, 2006b). An LCA study combines the technical description of value chains with the understanding of

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causal mechanisms from human interventions to environmental changes. This includes multidisciplinary approaches to assess global consequences over the three areas of concerns: human health, ecosystem quality and natural resources (JRC-EIS, 2011). While guidelines provide main principles and the corresponding assessment metrics for the first two areas of concern (Verones et al., 2017), the resource issue is still debated (Sonderegger et al., 2017) and remains the least consensual area of concern. The modeling of impact pathways based on a general mechanism, encompassing all resources, is an important issue to address (Frischknecht and Jolliet, 2016). But while for human health and ecosystem quality, impact models from specific disciplines (environmental toxicology, atmospheric science, etc.) are generally accepted to form the basis of the assessment models, the currently popular assessment models for resource depletion are based on "heuristic" considerations. This is in fact a slightly embarrassing situation, but, as we will show in this paper, there are disciplinary models available from fields like fishery and mining, and moreover, surprisingly, some of the existing "heuristic" proposals can be shown to correspond to those disciplinary models.

Sometimes, different strands of theoretical investigation suddenly converge, mutually reaffirming the original theories into a more general theory. A famous 19th century example is the merging of the theories on electricity, magnetism and light into electromagnetism. In this short communication, we draw attention to such a convergence movement in the area of the impact assessment of resource depletion, which is taking place now. We will start by briefly sketching the different partial theories and then move to their unification.

2. General impact assessment framework (1991–1993)

Life cycle impact assessment (LCIA) was conceptually developed in the early nineties, mainly through publications like Fava et al. (1991, 1993) and Heijungs et al. (1992). It relied on the use of characterization factors (CFs) that convert a quantified elementary flow (emission or extraction) into a contribution to an impact. The general structure was defined as

$$I_c = \sum_f CF_{c,f} \times m_f \tag{1}$$

where m_f is the size of the emission/extraction of type f (usually in kg, but occasionally in other units such as m^3 or MJ) and I_c is the impact category indicator result, such as climate change (in kg CO_2-equivalent) or human health (in yr or DALY). $CF_{c,f}$ is then the characterization factor that connects 1 unit of elementary flow f to a contribution to impact category c.

Usually, the number of elementary flows is much larger than the number of impact categories (hundreds or thousands against 1 or 10). As a further detail, the elementary flows may be specified by compartment (air, fresh water, etc.) and/or region (FR, NL, etc.), and as a consequence, it is possible to have CFs that are differentiated by compartment and/or region. Lists of CFs for different impact categories and for an increasing number of elementary flows were published from these days on. Nowadays, there are sets of CFs for dozens of impact categories, ranging from climate change to ocean acidification and from respiratory diseases to loss of ecosystem services.

3. Resource depletion assessment: a historical survey

3.1. Resource depletion potentials (1992–1995)

Guinée and Heijungs (1995) published a "proposal" for the construction of CFs for abiotic and biotic resources on the basis of an abiotic depletion potential (ADP) and a biotic depletion potential (BDP). Based on heuristic reasoning ("both reserves and deaccumulation … should somehow be included in an equation … indicating the seriousness of depletion") and formal mathematics (unit independence), they offer a formula for assessing resource depletion on the basis of a characterization factor that has deaccumulation (similar to production) P_f in the numerator, and reserve (measured in some way) R_f squared in the denominator:

$$CF_{RD,f} = const \times \frac{P_f}{R_f^2} \tag{2}$$

In fact, on formal arguments, they argued that the expression

$$CF_{RD,f} = const \times \frac{P_f^y}{R_f^{y+1}} \tag{3}$$

with $y > 0$, would make sense. The choice $y = 1$, leading to the P/R^2 type of formula was then made as "a practical suggestion", "confirming" the more speculative schemes from Heijungs et al. (1992) and Fava et al. (1993).

Guinée and Heijungs (1995) developed this approach both for abiotic and for biotic resources

$$\begin{cases} I_{AD} = \sum CF_{AD,f} \times m_f \\ I_{BD} = \sum CF_{BD,f} \times m_f \end{cases} \tag{4}$$

where I_{AD} is the score for abiotic depletion and I_{BD} is score for biotic depletion. For the constant *const*, they used the same expression for a reference flow which was antimony for abiotic depletion. The resulting score was then expressed in kg Sb-equivalent. This is often used in LCA and it is the recommended approach for the environmental product footprint in an EU context (Fazio et al., 2018). For biotic resources they did not propose a concrete reference. Indeed, the abiotic part was cited, used and elaborated far more than the biotic part (see, e.g. Guinée (1995), Hauschild et al. (2013), and van Oers and Guinée (2016)).

3.2. Depletion potentials as derivatives (1997)

In a university report, Heijungs et al. (1997 p. 34–36) discussed how a non-linear "dose-response" type model for describing the relation between resource use and depletion impact can be used to derive CFs. This is the first proposal to use a partial derivative for resource impact assessment and to provide a disciplinary foundation of the ADP approach. In particular, they showed how a quite reasonable assumption about such a model would lead to a CF with the extraction in the numerator and the square of the reserve in the denominator. In our notation, the "dose" is the production P_f and the response is some damage D due to total production, and the "dose-response" is a function $D = D(P_1, P_2, \ldots)$. Non-linearity is introduced in a very simple way: as a parabolic function:

$$D = \sum_f \left(\frac{P_f}{R_f}\right)^2 \tag{5}$$

From this general (non-LCA) relation, CFs for use in LCA are derived as partial derivatives:

$$CF_{RD,f} = \frac{\partial D}{\partial P_f} = \frac{2P_f}{R_f^2} = const \times \frac{P_f}{R_f^2} \tag{6}$$

The parabolic shape is of course a strong assumption here, but we believe it is not unreasonable. Perhaps it is valid within a limited range of values.

3.3. Other related work (1997–2017)

In response to these initial developments, several changes were proposed by various authors. One point of concern was the considered reserve. Guinée and Heijungs (1995) and van Oers et al. (2002) used the ultimate reserve, the crustal content of the element whereas JRC-EIS (2011) decided considering the reserve base (available resources with current practices). Schneider et al. (2015, 2011) considered in addition to the ultimate reserve the anthropogenic one (raw materials stored in the technical system). Another proposed change is the splitting (van Oers et al., 2002) of mineral and energetic resources into two impacts. See van Oers and Guinée (2016) for details. These changes have important consequences for the results, but the mathematical relationship remains identical in all these works: the extraction to reserve squared ratio.

Besides such variations within the P/R^2 framework, completely different methods were proposed and applied to assess resource depletion issues. For instance, the future efforts were addressed by taking into account the decrease of ore grade and corresponding surplus energy requirement (Goedkoop and Spriensma, 2001; Müller-wenk, 1998), associated cost increase (Goedkoop et al., 2013), or the extra amount of ore mined per additional unit of resource extracted (Vieira et al., 2017). Another example of a completely different principle is based on thermodynamic accounting (Dewulf et al., 2007) in term of exergy. A third example is the supply risk based on the criticality concept (Sonnemann et al., 2015). Dewulf et al. (2015) and Sonderegger et al. (2017) provide more comprehensive reviews. In this paper, we will further restrict the focus to the P/R^2 approach.

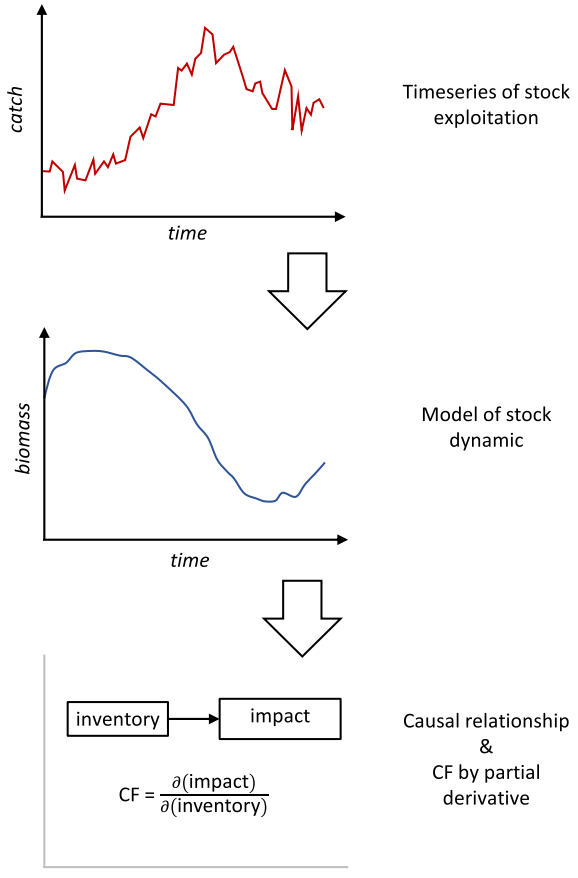

Fig. 1. Schematic of the CF derivation from bottom-up model.

3.4. Characterization factors from bottom-up models

Fig. 1 illustrates the approach used to define CFs from bottom-up model. Based on empirical data simulating the evolution of the exploitation rate, stock dynamics models have been proposed in the literature. It is thus possible to define a mathematical relationship linking the human intervention (the resource extraction) to the impact (the stock depletion). The partial derivative is then used expressing the marginal change and determining the CFs.

In this context, the development of new model of the involved mechanisms is not needed, so CFs are based on the knowledge from the relevant domain. In addition, the marginal approach is now one of the consensual way determining CFs (Frischknecht and Jolliet, 2016; Hauschild and Huijbregts, 2015). All of this supports the use of this approach.

3.4.1. Population dynamics (2018)

Recently, Hélias et al. (2018) applied this procedure for biotic resources. They used the theory of population dynamics of fish stocks to derive an expression for CFs of fish. The standard model by Schaefer (1954) expresses the rate of change of a population size (R_f) of fish type f as a differential equation

$$\frac{dR_f}{dt} = -P_f + r_f R_f\left(1-\frac{R_f}{K_f}\right) \tag{7}$$

Here r_f and K_f are species-dependent parameters (the symbols r and K are customary in the population dynamics literature and correspond to the intrinsic growth rate and to the carrying capacity of the habitat respectively, see Hélias et al. (2018) for details). This model adds in the balance between deaccumulation (P_f) and maximal regeneration ($r_f R_f$), the limitation of the habitat. This is done by introducing the depleted stock fraction (DSF, in bracket in Eq. (7)) which is taken as the damage indicator. The associated elementary flow is a mass of fish removed from the sea, that means a decrease of R_f. In steady-state ($\frac{dR_f}{dt} = 0$) we have:

$$DSF_f = \frac{P_f}{r_f R_f} \tag{8}$$

The characterization factor is then derived from the resulting expression:

$$CF_{FD,\,f} = -\frac{\partial DSF_f}{\partial R_f} = \frac{P_f}{r_f R_f^2} = const_f \times \frac{P_f}{R_f^2} \tag{9}$$

In other words, from a standard model in population dynamics, CFs can be derived for fish (and, we conjecture, for other biotic resources as well) which behave like P/R^2. One small note is that the constant may differ per population of fish.

3.4.2. Hubbert peak (this paper)

Population dynamics models used in fisheries represent external constraints (catch) and internal properties (size and characteristics of the stock) to assess resource availability. The purpose of the modeling for abiotic resource is similar: the estimation of resource availability in accordance with current production and stock description. It is interesting to look at the parallel we can draw.

The Schaefer population dynamics model is based on the very common logistic function. This relation describes an initial exponential increase, which is then slowed down to a limit value. In use for nearly two centuries, the logistic curve is applied in many domains such as stock management, ecology, biology, chemistry and economics. This is also the relation used in the Hubbert peak theory (Hubbert, 1981, 1956) and it is remarkable that the Schaefer and Hubbert models date

back to the same period. In the Hubbert curve model, the extraction rate P_f is a function of the cumulated mass of extracted resource since the beginning of the exploitation (Q_f):

$$P_f = \frac{dQ_f}{dt} = b_f\, Q_f\left(1 - \frac{Q_f}{U_f}\right) \tag{10}$$

The parameter b_f is the intrinsic growth rate of cumulative extraction (in time^{-1}). This shape parameter of the Hubbert model defines the spreading over the time of the curve and is constant for a given resource. U_f is the initial ultimately extractable reserve. With $Q_f = U_f - R_f$ (R_f is the current reserve), this is rewritten as follows

$$P_f = b_f\, R_f\left(1 - \frac{R_f}{U_f}\right) \tag{11}$$

Note that the Hubbert equation is similar to the Schaefer one at steady-state when considering an equivalence between K_f (viewed as the maximal size of the population) and U_f.

The estimation of resources availability is a highly discussed topic. When some authors highlight the urgency of the situation (Ali et al., 2017) others are less pessimistic, without dismissing the depletion issue (Tilton et al., 2018). All These positions can be roughly synthetize through the establishing of the main driver of the production rates between supply driven resources (where the depletion is a threat) or demand driven ones (where the market's flexibility makes it easier to adapt). Wellmer and Scholz (2017) discuss this point and underline that a Hubbert shape model hardly predicts peak time without a knowledge of the reserve or that the peak has to be passed for good fitting. We are not discussing here the interest of the Hubbert model to predict the ultimately recoverable reserve or the year of the extraction peak. This model shape fits well numerous observed dynamics of abiotic resource consumptions (although it is sometimes necessary to describe each type of stock independently as silver from dedicated mines with high-grade ores and silver as co-product from copper mines with therefore low-grade ores). We use the shape of the model to describe the current depleted resource fraction ($DRF_f = 1 - \frac{R_f}{U_f}$)

$$DRF_f = \frac{P_f}{b_f\, R_f} \tag{12}$$

This fraction equals to zero for a never exploited resource and tends towards one with the depletion. Note that there is, from a conceptual point of view, an analogy with the potential affected fraction of species (PAF) and indirectly with the potential disappeared fraction of species (PDF) used for the ecosystem quality area of concern. They represent the fraction of individuals of species (PAF) or the fraction of species in the ecosystem (PDF) missing in the nature (see Woods et al. (2018) for details about correspondences between PAF and PDF).

DRF_f is taken as the impact to assess for the resource depletion. The inventory flow is then a mass of extracted resource, removed from the current reserve R_f. The use of the marginal approach relates the marginal change of the impact according to the marginal change of the inventory. The use of partial derivative therefore makes it possible to define the CF of the resource depletion on the basis of the Hubbert theory:

$$CF_{HD,\,f} = -\frac{\partial DRF_f}{\partial R_f} = \frac{P_f}{b_f\, R_f^2} = const_f \times \frac{P_f}{R_f^2} \tag{13}$$

where we have changed the subscript *AD* from the classical abiotic depletion to *HD* for the one based on the Hubbert peak theory.

4. Empirical comparison of classical and Hubbert-based ADP

To compute CFs for both approaches with shared data, we used the work of Sverdrup et al. (2017), which provides consistent estimates of descriptors for 29 mineral reserves, and allows for the computation of both classical ADPs and Hubbert-based ADPs from the same data source. The ultimate recoverable reserves (URR) estimated are used as U_f (named "URR estimated by extractable amount ore quality grading" by Sverdrup et al. (2017), see Table 2), it also gives estimations of the cumulative extracted amount Q_f ("approximately amount dug up before 2010" by Sverdrup et al. (2017), Table 2), and allows to determine the current reserve R_f. The b_f parameters are determined from the expected maximum production rates (M_f, also provided by these authors, "P_{MAX}" in Table 3), with the relation $b_f = \frac{4M_f}{U_f}$ obtained from the logistic model equation (see for example Equation (4) in Sverdrup et al. (2014)).

The difference between the two approaches, $CF_{AD,\,f}$ and $CF_{HD,\,f}$, lies in the constant part of the equations with a fixed (antimony-based) unit conversion factor for CF_{AD} and a resource-specific parameter b_f for CF_{HD}. The two CF values are thus not directly comparable. But we can study their correlation, visually in Fig. 2, and statistically through the correlation coefficient $r = 0.99$ with $p - \text{value} \ll 0.001$ (based on the Pearson correlation between the logarithms of the two sets of CFs).

In the Hubbert model, this shape parameter b_f gives the intrinsic speed of the depletion: for a given U_f, a value ten times bigger means a depletion ten times faster. Values are distributed between 5×10^{-3} yr^{-1} for platinum to 7.7×10^{-2} yr^{-1} for tungsten. So, b_f varies over no more than two orders of magnitudes (e.g. the extraction peak of resources will occur in decades or centuries, see peak estimates in Sverdrup et al. (2017)) over the set of resources considered. In contrast, the current reserves (R_f) and the extraction rates (P_f) are spread over seven orders of magnitude (the boundaries values are between 2.7×10^4 t for germanium and 2.4×10^{11} t for iron for R_f, and between 1.2×10^2 t × yr^{-1} for tellurium and 1.3×10^9 t × yr^{-1} for iron for P_f). That means the CF values are mainly determined by these two parameters. Therefore, while theoretically Hubbert theory-based ADPs have a better theoretical foundation than the more heuristic original ADPs, the original ADP is a very good estimator for the CF derived as a marginal depletion characterization factor from the Hubbert curve.

5. Conclusion

The ADP was initially proposed on the basis of pragmatic and useful reasoning, before the marginal versus average approaches classification. This paper adds a new foundation for the ADP. Considering ADP as a marginal approach applied on resource dynamic models offers interesting perspectives. This implies that the CF design is based on a model which was developed in the relevant research fields, like it is for other impact categories. The models we have discussed suggest a similar approach for biotic and abiotic resources. Finally, this could contribute to a more consensual pathway for the resource area of concern, which is a hot topic in LCA (Sonderegger et al., 2017). Interestingly, the logistic model used in the Hubbert peak theory is also used in a very different LCIA method for assessing the depletion of resources, relating to damage cost based on surplus cost (Vieira et al., 2017).

Another point of interest could be a marginal approach on more complex models, combining the extraction and the recycling dynamics. However, this changes the assessed stock: it would be a wider one, merging the extractable reserve in the environment and the quantity usable in the technosphere (anthropogenic stock). This approach has thus to be discussed further and the associated models define.

The heuristic arguments that lead to the ADPs in the early nineties (Fava et al., 1993; Guinée and Heijungs, 1995; Heijungs et al., 1992) are backed up by a deeper theoretical foundation from the relevant disciplines, both for biotic resources (Hélias et al., 2018) and for abiotic

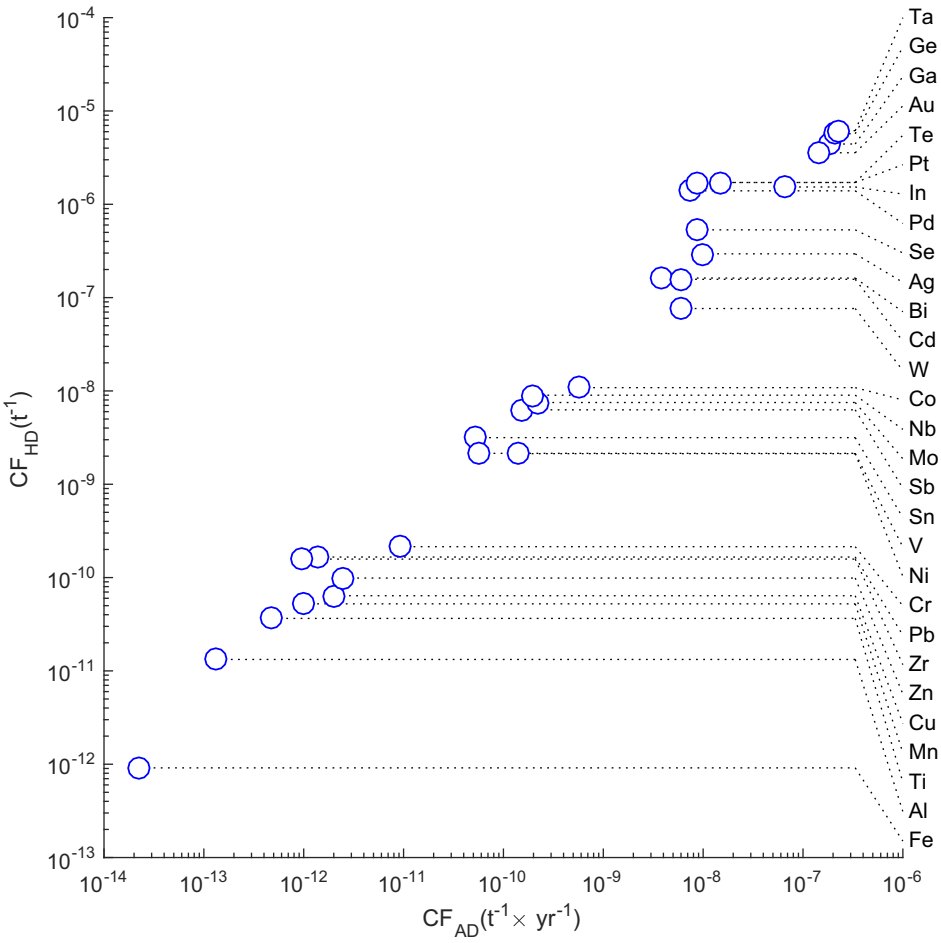

Fig. 2. Scatterplot (in log-scale) of CF_{HD} versus CF_{AD} for 29 mineral resources, see element symbols on the right. For CF_{AD} we have taken $const = 1$.

resources (this paper). Moreover, the resource depletion potential design now fits better in the overall framework of LCIA, where CFs are partial derivatives from dose-response type of models (Frischknecht and Jolliet, 2016).

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